An algorithm for tracking APEX spectral stability by means of the In-Flight Characterization facility (IFC)

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Originally published at:
D'Odorico, P; Alberti, E; Dell'Endice, F; Hueni, A; Itten, K I (2009). An algorithm for tracking APEX spectral stability by means of the In-Flight Characterization facility (IFC). In: 6th EARSeL SIG Workshop on Imaging Spectroscopy, Tel-Aviv, Israel, 16 March 2009 - 19 March 2009.

AN ALGORITHM FOR TRACKING APEX SPECTRAL STABILITY BY MEANS OF THE IN-FLIGHT CHARACTERIZATION FACILITY (IFC)

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KEY WORDS: Imaging Spectroscopy, Sensor Calibration, APEX

ABSTRACT

During their life span, imaging spectrometers are likely to be affected by deviations in spectral performances. Such fluctuations are mainly due to vibrations and temperature/pressure changes at the moment of launch or aging of the instrument. Prior to taking the spectrometer to the laboratory for a time-consuming re-characterization and re-calibration, it is good practice to monitor its spectral performance in-flight. For the Airborne Prism Experiment (APEX) spectrometer, this can be achieved by means of an onboard In-Flight Characterization (IFC) facility. IFC data are acquired at closed shutter with a stable input signal coming from a 75 W Quartz Tungsten Halogen (QTH) lamp. A filter wheel is interposed in the optical path leading to the detector; the spectral filters mounted on the wheel are characterized by a number of narrow spectral features. In this paper the development and tuning process of an algorithm to be used for the spectral stability monitoring of APEX is presented. The study is based on simulated IFC data and aims at identifying a spectrum-matching technique to be included in the final algorithm. In this context four spectrum-matching methods are tested in a varying range of simulated measurement conditions. We found that the methods employing the correlation coefficient and the RMSD as merit functions are more suitable and robust approaches for the estimation of the wavelength shift.

1. INTRODUCTION

Today, an increasing number of applications are benefiting from the improved spectral resolution offered by imaging spectrometers. A great number of narrow and contiguous spectral bands allows the exploitation of information, which would otherwise be lost when imaging with broadband sensors. Natural or artificial elements occurring on the earth surface or in the atmosphere can be identified by means of the spectral position, depths and shape of characteristic absorption features present in their spectra. To grant the reliability of the information retrieved, an accurate instrument spectral and radiometric calibration needs to be carried out at regular intervals (Guanter et al. 2007; Guanter et al. 2006).

Prior to operation, imaging spectrometers undergo a lengthy characterization procedure to take place usually in a controlled laboratory environment. In this occasion the full set of system parameters are measured to check their compliance with spectral, radiometric and geometric system requirements. It should be mentioned that spectral characterization has been recognized as the most elaborate of all procedures (Gege et al.). Once the sensor becomes airborne or spaceborne, vibrations, changes in instrument temperature/pressure and aging, may trigger undesired modifications in instrument spectral characteristics (Gao et al. 2004; Guanter et al. 2006). The spectral degradation of the sensor has as a direct consequence the deviation of band centre wavelengths from the nominal band positions. Besides, aberrations in the spectrograph collimator and imaging optics or misalignments of the detector array in the instrument's focal plane can cause a non-linearity of the observed centre wavelength shift in the across-track direction, known as spectral smile (Neville et al. 2008).

Given these considerations, it is easy to understand why the increase in sensor's spectral performance has generated the need for an

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increased spectral stability monitoring, which cannot be limited to periodic laboratory characterizations. To the author's knowledge, past efforts of in-flight spectral stability monitoring for airborne spectrometers are restricted to spectrum-matching techniques based on observed feature present in the imaging data (Brazile et al. 2008; Gao et al. 2004; Guanter et al. 2007; Neville et al. 2008). These features are commonly atmospheric features, such as water vapour, oxygen and carbon dioxide bands, and solar Fraunhofer lines. The key advantage of having spectral characterization equipment onboard an airborne spectrometer is that the same set of measurements can be acquired when the instrument is on the ground, e.g. in the hangar, and in-flight, thus a direct comparison becomes feasible. Furthermore, a comparison among different characterization runs performed in-flight provides insights in the relative stability of the instrument. Onboard characterization facilities are already common practice for spaceborne sensors, where an on-ground re-characterization is not feasible (Delwart et al. 2007; Montgomery et al. 2000).

In this paper, the In-Flight Characterization facility (IFC) onboard the Airborne Prism Experiment (APEX) is presented. APEX is a pushbroom imaging spectrometer currently under development by a Swiss/Belgian consortium under the authority of ESA's PRODEX programme (Itten et al. 2008). APEX is operating between 380 and 2500 nm with 534 contiguous spectral bands in full spectral mode, with the option of binned band configurations meant to satisfy application-specific requirements. The total field of view (FOV) is 28° with a total of 1000 spatial elements across-track. Thanks to the flexibility in spectral sampling and to the possibility of accurate spectral stability monitoring by means of onboard characterization equipment, this instrument is meant to become an important simulator and calibrator for existing and upcoming space missions as well as a reference for other airborne instrument (Itten et al. 2008).

This paper presents the development and tuning of the algorithm to be employed for the spectral stability monitoring of APEX. The objective of the algorithm is the estimation of center wavelength (CW) shifts from IFC data at sub-pixel level. A number of methods have been investigated and validated. Disturbance effects that may arise is an opto-electronic system, such as the variations of the spectral channel Full Width Half Maximum (FWHM) and the effect of noise, have been accounted for in the simulations, and their effect quantified.

2. THE IN-FLIGHT CHARACTERIZATION (IFC) CONCEPT

The In-Flight Characterization (IFC) facility of APEX comprises on-board calibration equipment allowing the monitoring of the absolute and relative stability of spectral and radiometric instrument characteristics during the operation phase. IFC measurements can occur independently from the sensor-sun geometry and do not interfere with scientific data acquisition as the shutter will remain close and the signal will be generated by an internal stabilized QTH (Quartz Tungsten Halogen) 75W lamp. In order to optimize the spatial and spectral properties of the IFC illumination, a KG4 filter (to reduce the light intensity in the SWIR) and a holographic diffuser (to ensure a homogeneous illumination on the detector array) are placed at the exit port of the lamp housing. An optical fibre guides the light from the lamp towards the illumination optics placed in the Optical Sub-Unit (OSU). At the position where the fibre enters the OSU a hermetically sealed connector is inserted to allow a sealed fibre throughput. Imaging optics project the fibre light onto a second diffuser to further improve the uniformity of the illumination. The light level of the lamp is monitored with a detector placed in the OSU thermally stabilized environment. The detector will control the lamp power in a closed loop. Furthermore, FOV adjustment optics are needed to match the light beam coming from the IFC with the FOV of the OSU spectrometer. During the in-flight calibration, a mirror will be shifted in the optical path of the imaging spectrometer to reflect the light that is generated in the IFC towards the OSU. A filter wheel assembly is mounted in front of the first lens of the OSU; it contains the filters necessary for the spectral characterization and filters that are used to prevent saturation of the detectors.

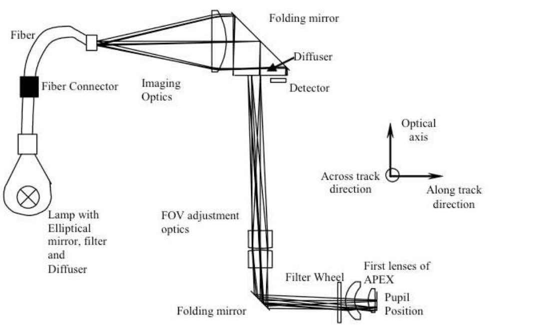

Figure 1. Optical design of the In-Flight Characterization facility (IFC). Source: courtesy of OIP.

Spectral filters, used to evaluate the spectral stability of the detector, occupy four positions on the filter wheel. Three are band pass filters, which block the light for most of the electromagnetic spectrum except around the bandpass wavelength at 694, 1000, and 2218 nm, respectively. The fourth spectral filter is a NIST standardized rare Earth filter SRM 2085 exhibiting a spectrum rich of narrow and well-distributed absorption features (Figure 2).

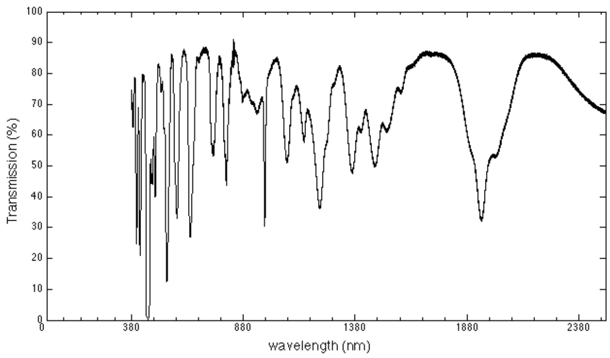

Figure 2. Transmission profile of the SRM-NIST spectral filter mounted on the IFC wheel.

3. DATA & METHODS

Four different spectrum-matching algorithms were tested as part of this analysis. The four techniques base on the optimization of four different merit functions, which compare individual spectral features previously extracted from the respective spectra by means of indices. The methods and the respective merit functions to be optimized are given hereafter:

Correlation method (CORR)	$f = \dfrac{\mathrm{cov}(S_{ref}, S_{test})}{\sigma_{S\_ref}\sigma_{S\_test}}$	(1)
Root Mean Square Deviation method (RMSD)	$f = \sqrt{\dfrac{1}{N}\sum_{i=1}^{N}\left(S_{i,ref} - S_{i,test}\right)^2}$	(2)
Peak-to-Peak method (PTP)	$f = \lambda_{peak,ref} - \lambda_{peak,test}$, *where* $\lambda_{peak} = \lambda(\max(S))$	(3)
Centre of Gravity method (COG)	$f = \lambda_{cog,ref} - \lambda_{cog,test}$, *where* $\lambda_{cog} = \dfrac{\sum_{i=1}^{N}\lambda_i S_i}{\sum_{i=1}^{N} S_i}$	(4)

The algorithms are tested using datasets resembling those we can expect to acquire via the IFC. The simulation model generating these datasets is presented hereafter. In a first step a high-resolution signal is obtained by multiplying the QTH lamp signal with the transmission profile of the SRM spectral filter. A convolution function (Equation 5) convolves the high-resolution spectrum to sensor characteristics using a Gaussian approximation of the sensor spectral response functions (SRF). The convolved signal levels S_i in a band i are calculated as follows:

$$S_i = \frac{\int_{j=1}^{N} S(\lambda_j) r_i(\lambda_j)\Delta\lambda_j}{\int_{j=1}^{N} r_i(\lambda_j)\Delta\lambda_j} \tag{5}$$

where $S(\lambda_j)$ is the signal value of the high-resolution spectrum at the j-th wavelength, $r_i(\lambda_j)$ is the spectral response function of the sensor's band i and the j-th wavelength and $\Delta\lambda_j$ is the interval between two subsequent sampling frequencies.

The convolution is repeated using different SRFs with progressively shifted CW so as to obtain the spectra, which would be recorded by an instrument with slightly changed spectral properties. A random noise component, in the order of those expected from the unsystematic signal of the dark current (DC), is added to the spectra to simulate the physical system behaviour. The obtained pool of spectra represents the reference dataset. In a second step, a test dataset is generated by selecting few specific wavelength shifts to impose to the nominal CWs prior to convolution. Additionally, we introduce a change in FWHM in which we decrease or increase its value by dividing or multiplying by factor 1,5. The FWHMs of an optical system depend on the characteristics of the system itself (e.g. number and type of optical surfaces, respective coatings, detectors). A deviation of these values would involve a significant modification of the optical system and is thus unlikely. Nevertheless, the analysis of this effect remains mandatory in order to obtain a full picture of the methods' robustness. As was the case for the reference spectra, also our test spectra are contaminated with random noise. The obtained test dataset stands for what in an operational scenario would be the in-flight IFC measurements acquired with the instrument whose spectral stability is under investigation. Eventually, by means of the chosen spectrum-matching algorithm, each individual test spectra is compared with the pool of reference spectra. The iterative comparison reaches a halt once the best fit with a reference spectrum is found. By means of the CWs associated with the best match we are able to retrieve the shift from nominal values, as estimated by the employed spectrum-matching technique.

4. RESULTS AND DISCUSSION

The four methods presented above for the determination of wavelength shift were evaluated and compared. Their robustness was assessed based on their sensitivity to a number of variables. It should be noted that all the results presented hereafter are averaged over 100 noise iterations.

First, the sensitivity of the methods to the shape of the spectral feature was investigated based on three SRM-NIST features (Figure 3). The mean errors, calculated as the mean of the absolute deviations of derived shifts from imposed shifts, of the four methods are summarized in Table 1, accompanied by the respective standard deviations. For this analysis the imposed shift was kept stable for all three features. Nevertheless, when comparing results across features one should consider the different meaning of the shift in relation to the FWHM of the bands covered by the specific feature. APEX average FWHMs over the three regions covered by the three features were 1.85, 2.4 and 3.61 nm, respectively.

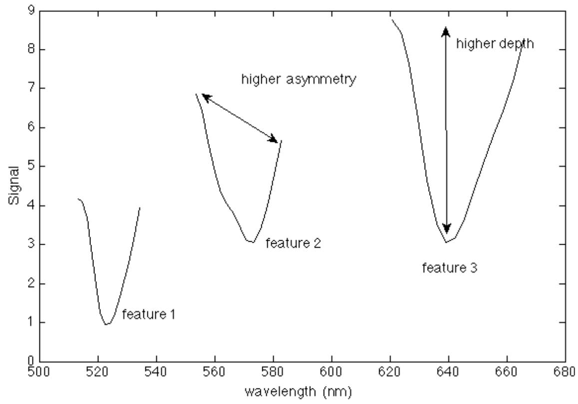

Figure 3. SRM-NIST features considered for this study.

Table 1 Evaluation of different spectrum-matching techniques to derive the wavelength shift (Imposed shift: 0.1nm, SNR: 250)

Methods	Feature 1 513-534 nm		Feature 2 553 -583 nm		Feature 3 620 -665 nm	
	abs mean error (nm)	Std (nm)	abs mean error (nm)	Std (nm)	abs mean error (nm)	Std (nm)
CORR	0.0010	0.0032	0.0021	0.0046	0.0013	0.0036
RMSD	0.0009	0.0030	0.0018	0.0043	0.0013	0.0036
PTP	0.1021	0.0534	0.0924	0.0690	0.0831	0.0552
COG	0.1106	0.1257	0.0139	0.0180	0.0859	0.1117

Table 1 reveals that the correlation (CORR) and the root mean square deviation (RMSD) methods exhibit similar performances, characterized by very low mean errors, in the order of 1-2%, for all three features. The Peak-to-Peak (PtP) method performs poorly with mean errors reaching 100%, however was found out to be not affected by the shape of the feature. The Centre of Gravity (COG) method instead exhibits a high sensitivity to the shape of the feature, improving its rather poor performance of a factor ten for feature two (553-583 nm).

In the next step the sensitivity of the methods towards Signal to Noise Ratio (SNR) was investigated. Figure 4 indicates how the first three methods (CORR, RMSD, PtP) are not significantly affected by a change in SNR. On the other hand the COG method exhibits an improvement in performance, decreasing the overestimation of the shift with higher SNRs, which however is feature-dependant as can be seen in Figure 5.

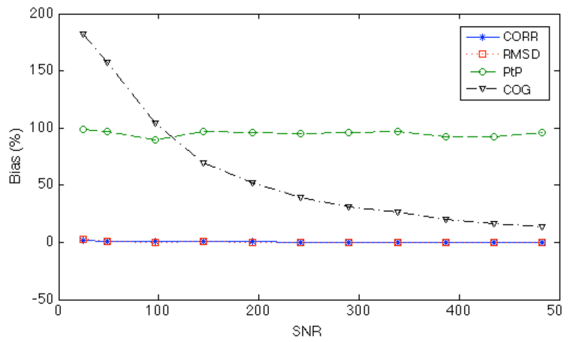

Figure 4. Sensitivity of the four methods to Signal to Noise Ratio (SNR).

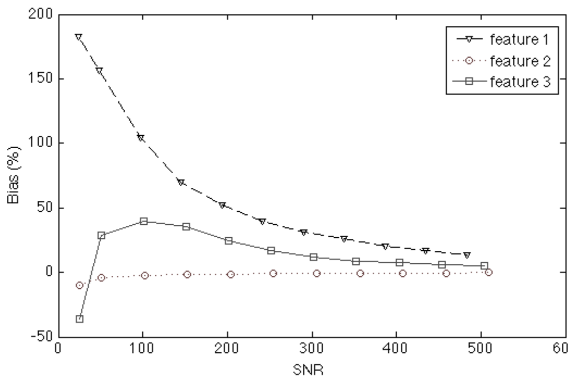

Figure 5. Sensitivity of the Center of Gravity (COG) method to Signal to Noise Ratio (SNR) and to the shape of the feature.

Introducing different magnitudes of spectral shift at constant SNRs, allowed assessing the influence of the degree of the shift for each method. Results for the first feature are presented in Figure 6. Figure 7 confirms also in this case the influence of the feature shape on the performance of the COG method.

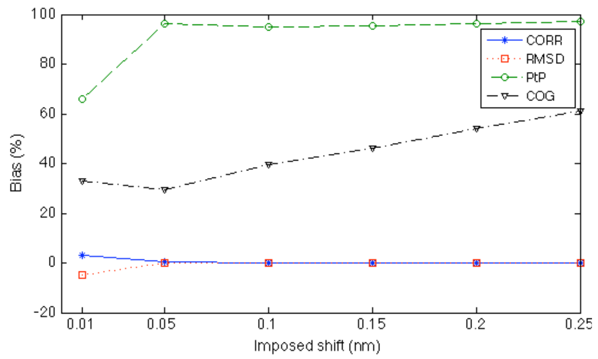

Figure 6. Sensitivity of the four methods to magnitude of shift.

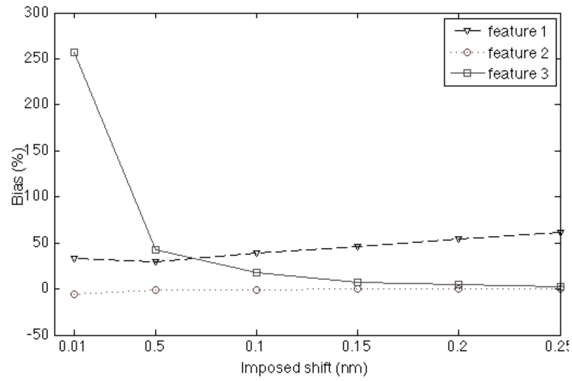

Figure 7. Sensitivity of the Center of Gravity (COG) method to magnitude of shift and to the shape of the feature.

In the case study described hereafter we assessed the sensitivity of the methods towards a change in FWHM. In generating the test spectra, the signal was thus convolved with SRFs whose CWs had been shifted and FWHMs increased or decreased by a factor of 1.5. Table 2 presents the biases obtained for each feature with the four methods, calculated as the mean of the deviations of derived shifts from imposed shifts. Generally speaking, a change in FWHM increases the bias obtained by each method for all features, but no systematic trend was identified. Once again the shape of the feature strongly affected the results for the COG method.

Table 2. Sensitivity of the four methods to changing FWHM. (Imposed shift: 0.1nm, SNR: 250)

	Method	Bias (%) nominal FWHM	Bias (%) FWHM/1.5	Bias (%) FWHM*1.5
Feature 1 513-534 nm	CORR	0.2	4.4	-10.3
	RMSD	-0.1	4.2	-10.2
	PTP	94.9	121.3	56
	COG	39.4	-81	696.6
Feature 2 553 -583 nm	CORR	-0.3	-0.1	-3.5
	RMSD	-0.2	1.7	-6.3
	PTP	80.4	142.2	33.6
	COG	-0.9	7.8	-17.4
Feature 3 620 -665 nm	CORR	-0.1	6.1	-11.6
	RMSD	-0.3	0.5	1.5
	PTP	78.7	58.7	168.7
	COG	17.3	391	-746.9

5. CONCLUSIONS

A number of studies have employed individual spectrum-matching techniques in the context of spectral calibration of imaging spectrometers based on atmospheric absorption features (Barry et al. 2001, 2002; Gao et al. 2004; Neville et al. 2008). To the author's knowledge to this date, none of these studies included an assessment and comparison of the performances of each method over different measurements conditions.

This study revealed the superiority of the methods employing the correlation coefficient and the RMSD as merit-functions, for the purpose of wavelength shift estimation based on APEX IFC. The latter methods performed best over all range of studied conditions, which included changing feature shape, varying SNR, increase of the degree of shift and changing FWHM. On the other hand, the Peak-to-Peak method did not exhibit significant sensitivity to changing measurement conditions and performed poorly, in all cases. The Centre of Gravity method was found to be unreliable due to its high dependency on the shape of the feature. Further analysis is needed and foreseen to consolidate the above conclusions. Eventually, the best performing spectrum-matching method will be incorporated in the wavelength-stability-monitoring algorithm used for the processing of APEX IFC data.

6. REFERENCES

Barry, P.S., Shepanski, J., and Segal, C. (2001). HYPERION on-orbit validation of spectral calibration using atmospheric lines and an on-board system, Proc. SPIE, S. M. Descour Ed. , vol. 4480, Imaging Spectrometry VII, p. 231.

Brazile, J., Neville, R.A., Staenz, K., Schläpfer, D., Sun, L., & Itten, K. (2008). Towards scene-based retrieval of spectral response functions for hyperspectral imagers using Frauenhofer features. *Canadian Journal of Remote Sensing, 34*, S43-S58

Delwart, S., Preusker, R., Bourg, L., Santer, R., Ramon, D., & Fischer, J. (2007). MERIS In-flight Spectral Calibration. *International Journal of Remote Sensing, 28*, 479-496

Gao, B.C., Montes, M., & Davis, C. (2004). Refinement of wavelength calibrations of hyperspectral imaging data using a spectrum-matching technique. *Remote Sensing of Environment, 90*, 424-433

Gege, P., Fries, J., Haschberger, P., Schˆtz, P., Schwarzer, H., Strobl, P., Suhr, B., Ulbrich, G., & Jan Vreeling, W. Calibration facility for airborne imaging spectrometers. *ISPRS Journal of Photogrammetry and Remote Sensing, In Press, Corrected Proof*

Guanter, L., EstellÈs, V., & Moreno, J. (2007). Spectral calibration and atmospheric correction of ultra-fine spectral and spatial resolution remote sensing data. Application to CASI-1500 data. *Remote Sensing of Environment, 109*, 54-65

Guanter, L., Richter, R., & Moreno, J. (2006). Spectral calibration of hyperspectral imagery using atmospheric absorption features. *Applied Optics, 45*, 2360-2370

Itten, K.I., Dell'Endice, F., Hueni, A., Kneubühler, M., Schläpfer, D., Odermatt, D., Seidel, F., Huber, S., Schopfer, J., Kellenberger, T., Bühler, Y., D'Odorico, P., Nieke, J., Alberti, E., & Meuleman, K. (2008). APEX - the Hyperspectral ESA Airborne Prism Experiment. *Sensors, 8*, 6235-6259

Montgomery, H., Che, N., Parker, K., & Bowser, J. (2000). The algorithm for modis wavelength on-orbit calibration using the SRCA. *IEEE Transactions on Geoscience and Remote Sensing, 38*, 877-884

Neville, R.A., Sun, L., & Staenz, K. (2008). Spectral calibration of imaging spectrometers by atmospheric absorption feature matching. *Canadian Journal of Remote Sensing, 34*

ACKNOWLEDGEMENTS

This work has been carried out in the framework of the Hyperspectral Imaging Network (HYPER-I-NET) project, funded by the Marie Curie Actions of the Sixth Framework Programme (FP6).